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Use of Produced Water in Recirculating Cooling Systems at Power Generating Facilities

Deliverable Number 8
Applicability to Other Regions in the US

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Disclaimer

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Abstract

The purpose of this study is to evaluate produced water as a supplemental source of water for the San Juan Generating Station (SJGS). This study incorporates elements that identify produced water volume and quality, infrastructure to deliver it to SJGS, treatment requirements to use it at the plant, delivery and treatment economics, etc.

SJGS, which is operated by Public Service of New Mexico (PNM) is located about 15 miles northwest of Farmington, New Mexico. It has four units with a total generating capacity of about 1,800 MW. The plant uses 22,400 acre-feet of water per year from the San Juan River with most of its demand resulting from cooling tower make-up. The plant is a zero liquid discharge facility and, as such, is well practiced in efficient water use and reuse.

For the past few years, New Mexico has been suffering from a severe drought. Climate researchers are predicting the return of very dry weather over the next 30 to 40 years. Concern over the drought has spurred interest in evaluating the use of otherwise unusable saline waters.

Produced water is generated nationally as a byproduct of oil and gas production. Seven states generate 90 percent of the produced water in the continental US. About 37 percent of the sources[1] documented in the US Geological Survey's (USGS) Produced Waters Database have a TDS of less than 30,000 mg/l. This is significant because produced water treatment for reuse in power plants was found to be very costly above 30,000 mg/l TDS. For the purposes of this report, produced water treatment was assessed using the technologies evaluated for the San Juan Generating Station (SJGS) in Deliverable 3, Treatment and Disposal Analysis. Also, a methodology was developed to readily estimate capital and operating costs for produced water treatment. Two examples are presented to show how the cost estimating methodology can be used to evaluate the cost of treatment of produced water at power plants close to oil and gas production.

[1] This threshold value is based on a numeric sort of the data and is not weighted by produced water volume.

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Executive Summary

The purpose of this study is to evaluate produced water as a supplemental source of water for the San Juan Generating Station (SJGS). This study incorporates elements that identify produced water volume and quality, infrastructure to deliver it to SJGS, treatment requirements to use it at the plant, delivery and treatment economics, etc.

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For the past few years, New Mexico has been suffering from a severe drought. Climate researchers are predicting the return of very dry weather over the next 30 to 40 years. Concern over the drought has spurred interest in evaluating the use of otherwise unusable saline waters.

Nationally, produced water volume is dropping along with reduced conventional oil and gas production. New CBM development will likely dampen the decline in produced water volume in a number of states where there are large coal reserves such as Colorado, Wyoming and Montana. Seven states generated 90.1 percent of the produced water in 2002. Texas alone generated 35.5 percent of the produced water in the US during the same year.

USGS has compiled a Produced Waters Database. One of the important values of the data is that it shows the variability of the produced water resource. For example, produced water TDS in the database ranges from 500 mg/l to 400,000 mg/l. About 37 percent of the produced water sources in the database have a TDS value of less than 30,000 mg/l. This is significant because produced water treatment for reuse in power plants is not economically feasible above 30,000 mg/l TDS. Only basic chemistry is provided in the database, i.e. pH, sodium, potassium, calcium, magnesium, alkalinity, chloride and sulfate. Other chemical information of interest, such as silica, barium, ammonia, volatile organic constituents, etc. are not available.

High-efficiency reverse osmosis (HERO®) and brine concentrator (BC) technologies were evaluated for produced water treatment:

- HERO® + BC (waste brine disposed with ash and/or SO_2 scrubber sludge)
- HERO® + BC + evaporation ponds
- HERO® + BC + crystallizer

The applicability of these treatment systems depends on how a power plant is configured with respect to ash and SO_2 scrubber sludge disposal and whether the climate is suitable for evaporation ponds. It is also assumed that reactor-clarifier sludge could be combined with other treatment solids for disposal. In this analysis, all equipment was assumed to be new, i.e. no existing equipment is reassigned or refurbished for produced water treatment service.

The analysis was biased to maximize the recovery of the HERO® process and minimize the size of BC and crystallizer equipment and evaporation ponds. BC and crystallizer equipment is significantly more costly to install than the HERO® process (for a given flow rate) and more costly to operate. Evaporation ponds are capital intensive.

Capital cost was predicted for each configuration, for a range of feedwater rates (10,000 BPD to 100,000 BPD), and for seven different TDS scenarios ranging from 2,000 mg/l to 30,000 mg/l. The costs include equipment and installation plus 25 percent contingency to cover project unknowns. Also, because this analysis is general (not specific to any particular site), costs should be considered "conceptual level" with a +50/-35 percent range of confidence.

Operating costs were developed for each of the seven TDS scenarios. The analysis was designed to determine the performance and operating cost of a reactor clarifier, since its costs typically dominate other chemical costs. Reactor clarifier costs were averaged and added to the cost of other chemicals, power, membrane replacement, cleaning (RO membranes, BC internal surfaces and crystallizer internal surfaces as applicable), sludge/solids handling and onsite disposal, labor, and maintenance. Staffing to operate and maintain the treatment plant was adjusted (to determine labor costs) based on the size of the plant. Lastly, operating costs did not include capital recovery costs. These were purposefully left out to show how throughput capacity and TDS affect unit operating cost.

Adjustment factors are provided to determine the variability of operating costs. It is prudent to apply variations to general data until site-specific information can be assessed. Site-specific chemistry is required to rigorously evaluate treatability and costs. The approach developed here can be used to conceptually bracket operating costs.

Capital and operating costs for de-oiling/filtration facilities and three pipeline scenarios were also estimated separately.

Two plant examples are presented to show how the cost estimating charts could be used to evaluate the treatment of produced water at power plants close to oil and/or gas production.

8.1 Introduction

Produced water is generated nationally as a byproduct of oil and gas production. Seven states generate 90 percent of the produced water in the continental US. About 37 percent of the sources[1] documented in the US Geological Survey's (USGS) Produced Waters Database have a TDS of less than 30,000 mg/l. This is significant because produced water treatment for reuse in power plants was found to be very costly above 30,000 mg/l TDS. For the purposes of this report, produced water treatment was assessed using the technologies evaluated for the San Juan Generating Station (SJGS) in Deliverable 3, Treatment and Disposal Analysis. Also, a methodology was developed to readily estimate capital and operating costs for produced water treatment. Two examples are presented to show how the cost estimating methodology can be used to evaluate the cost of treatment of produced water at power plants close to oil and gas production.

8.2 Produced Water Generation Nationally

Produced water is a byproduct of oil and gas production, and depending on the site, a significant amount can be generated relative to the actual volume of production. This section outlines how produced water is formed and brought to the surface, where it is produced in the US and its basic chemistry.

8.2.1 How Produced Water is Generated

Produced water is brought to the surface when oil and gas are extracted from bearing formations. Oil and gas deposits form in ancient sediments of organic matter, e.g. in prehistoric ocean bottoms. In time, oil, gas and water co-mingle in the pores of sediment, and when oil and gas are brought to the surface, water is also lifted. Generally, for every barrel of oil, nine barrels of water are brought to the surface. Over time, the amount of water brought to the surface usually increases relative to oil and gas production.

In coal bed methane (CBM) production, gas is extracted directly from coal seams. To allow the gas to separate from the coal, water above and surrounding the coal must be extracted to reduce hydrostatic pressure to allow methane release (with the water). The amount of water brought to the surface (relative to methane gas) is highly variable and depends on site-specific geologic and hydrogeologic conditions. In CBM production, water generation is high at the outset and falls off over time.

8.2.2 Where Produced Water is Generated in the US

Refer to Table 8.1 for a summary of produced water generation in the continental US. The table, which was extracted from a report prepared by Argonne National Laboratory[2], identifies produced water generation in 31 states for the years of 1985, 1995 and 2002.

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[1] This threshold value is based on a numeric sort of datasets and is not weighted by produced water volume.

[2] J.A. Veil, M.G. Puder, D. Elcock and R.J. Redweik, Jr., "A White Paper Describing Produced Water From Production of Crude Oil, Natural Gas and Coal Bed Methane", prepared by Argonne National Laboratory for the US Department of Energy, National Energy Technology Laboratory, January 2004

For many of the states, produced water generation was estimated by using historic water-to-product ratios. Nationally, produced water volume is dropping along with reduced conventional oil and gas production.

The annual volumes prepared by Veil 2003 also include produced water that is treated and reused for water floods or steam floods in enhanced oil and gas production; therefore, this water is not available for downstream reuse.

Table 8.1
Annual Onshore Produced Water Generation by State (1,000 bbl)
Prepared by Argonne National Laboratory, 2004

State	1985[a]	1995[b]	2002[c]	Source
Alabama	87,619	320,000	99,938	State
Alaska	97,740	1,090,000	813,367	State
Arizona	149	100	88	Estimate
Arkansas	184,536	110,000	90,331	Estimate
California	2,846,078	1,684,200	1,290,050	Estimate
Colorado	388,661	210,600	133,005	Estimate
Florida	No data available	76,500	48,990	Estimate
Illinois	1,282,933	285,000	212,098	Estimate
Indiana	No data available	48,900	34,531	Estimate
Kansas	999,143	683,700	1,174,641	State
Kentucky	90,754	3,000	2,411	Estimate
Louisiana	1,346,675	1,346,400	1,079,805	State
Michigan	76,440	52,900	33,207	Estimate
Mississippi	318,666	234,700	286,532	State
Missouri	No data available	100	1,200	State
Montana	223,558	103,300	104,501	Estimate
Nebraska	164,688	61,200	51,191	State
Nevada	No data available	6,700	2,765	Estimate
New Mexico	445,265	706,000	112,934	State
New York	No data available	300	844	State
North Dakota	59,503	79,800	78,236	Estimate
Ohio	No data available	7,900	6,416	State
Oklahoma	3,103,433	1,642,500	1,252,870	Estimate
Pennsylvania	No data available	2,100	5,842	State
South Dakota	5,155	4,000	3,293	State
Tennessee	No data available	400	275	Estimate
Texas	7,838,783	7,630,000	5,031,945	State
Utah	260,661	124,600	84,791	Estimate
Virginia	No data available	300	550	Estimate
W. Virginia	2,844	6,000	4,284	Estimate
Wyoming	785,221	1,401,000	2,119,394	State
TOTAL	20,608,505	17,922,200	14,160,325	

[a] 1985 produced water volume (barrels) from API (1988).
[b] 1995 produced water volume (barrels) from API (2000).
[c] 2002 produced water volume data from state oil and gas agencies/websites unless estimated based on historic water-to-oil ratio.

Table 8.1 can be sorted into three tiers (refer to the summary below). The first tier of states generated 90.1 percent of the produced water in 2002 (volume greater than 813 MBPY[3]) – Alaska, California, Kansas, Louisiana, Oklahoma, Texas and Wyoming. Texas alone generated 35.5 percent of the produced water in the US in 2002. The next tier (78 MBPY to 813 MBPY) – Alaska, Arkansas, Colorado, Illinois, Mississippi, Montana, New Mexico, North Dakota and Utah – generated 8.5 percent of the produced water. The last tier (15 states) generated 1.4 percent.

	Tier Criteria MBPY	Daily Produced Water Volume BPD	Number of States	Fraction of Total Volume
Tier 1	>813	34,965,000	7	90.1%
Tier 2	78 to 813	3,294,000	9	8.5%
Tier 3	<78	537,000	15	1.4%
Total	----	38,796,000	31	100.0%

Clearly, opportunities for produced water reuse should be focused in Tier 1 states and secondarily in Tier 2 states. The treatment and reuse of produced water at SJGS is a good example of a Tier 2 opportunity.

Current market pressures to increase CBM development and production are accelerating produced water generation in many states. New CBM development should dampen the decline in produced water volume in a number of states where there are large coal reserves such as Colorado, Wyoming and Montana. Also note that produced water in Wyoming (refer to Table 8.1) has increased steadily as a result of CBM production. Refer to Figure 8.1 for a map of coal basins that produce (or could possibly produce) CBM. The map was prepared by ALL Consulting.[4]

8.2.3 Produced Water Chemistry

The USGS has compiled a provisional Produced Waters Database.[5] The database contains well information (well name, well owner, state location, township and section numbers, longitude and latitude, etc.) and basic produced water chemistry. Some of the information dates back 80 years. Chemistry data provided by Veil 2003 (conventional and CBM sources), ALL 2003 (CBM sources) and the author's work in California and New Mexico fall well within the envelop of data provided by the USGS database.

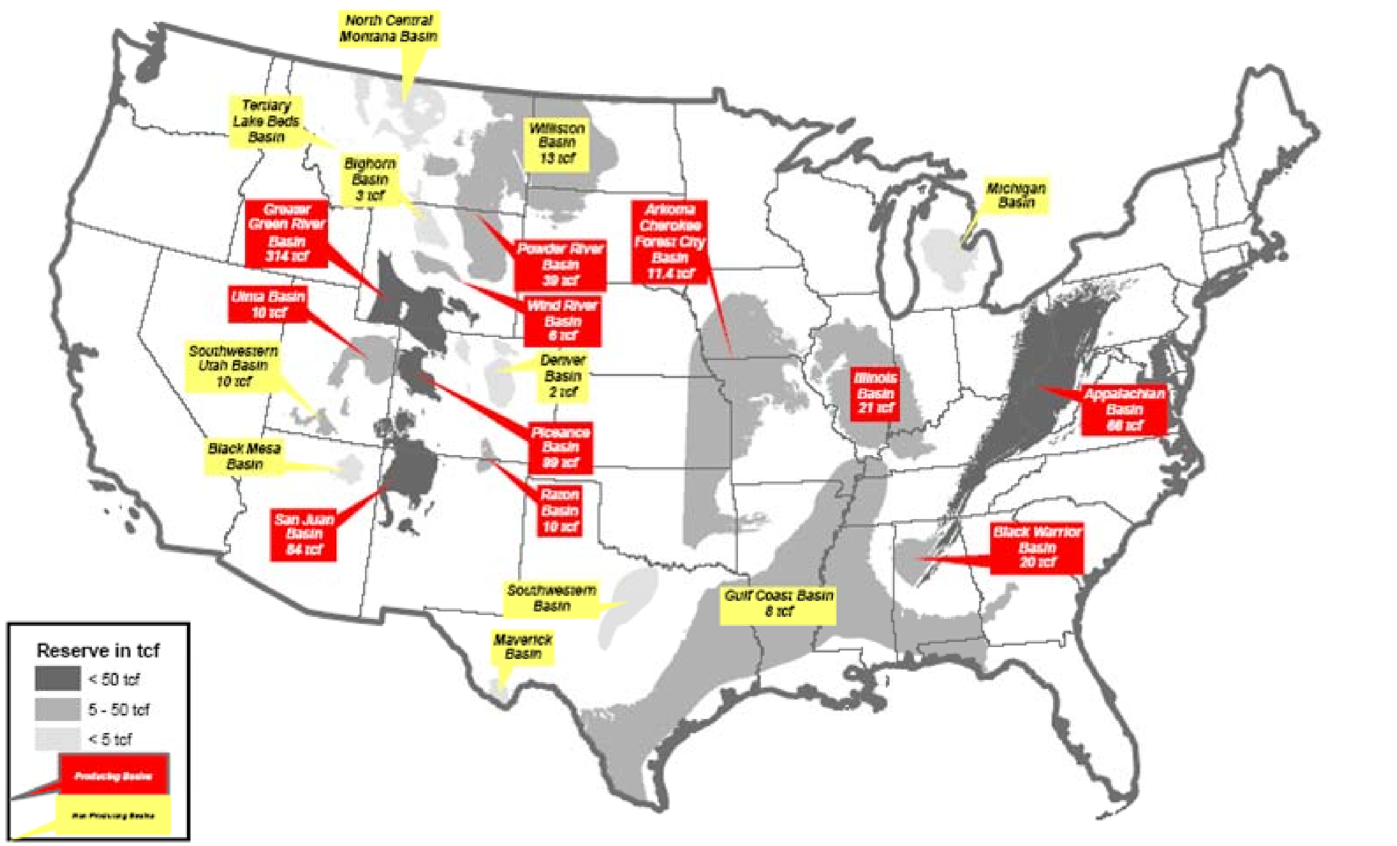
[3] MBPY corresponds to one million barrels of produced water per year – 1 MBPY is equivalent to 2,740 BPD or 80.0 gpm.
[4] "Handbook on Coal Bed Methane Produced Water: Management and Beneficial Use Alternatives", prepared by ALL Consulting for Groundwater Protection Research Foundation and for the US Department of Energy, National Energy Technology Laboratory, July 2003
[5] The data is considered provisional because it has not received the approval of the Director of the USGS and is subject to revision. The database, which was posted in May 2002, can be found on the USGS website at energy.cr.usgs.gov/prov/prodwat/.

Figure 8.1

Map of U.S. Coal Reserves/Basins

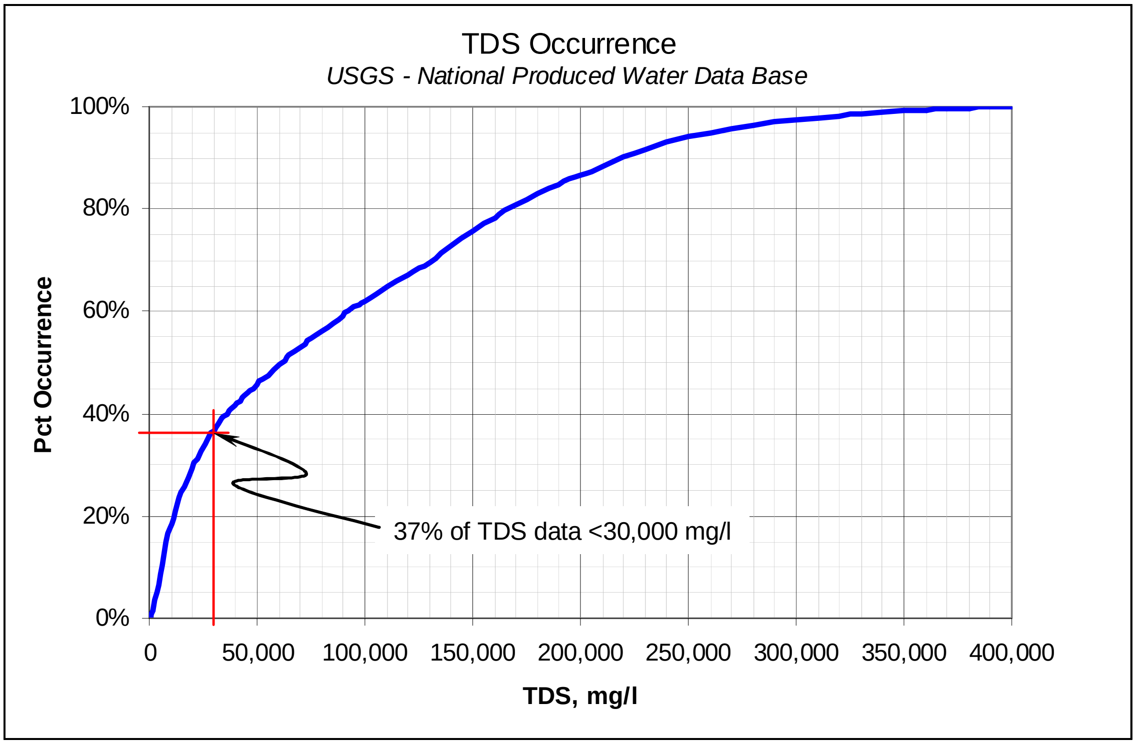
U.S. coal reserves and basins

Prepared by ALL Consulting, 2002



One of the important values of the data is demonstration of the variability of the produced water resource. For example, produced water TDS in the database ranges from 500 mg/l to 400,000 mg/l. Refer to Figure 8.2 for a distribution of TDS values. About 37 percent of the produced water datasets have a TDS value of less than 30,000 mg/l. This is significant because produced water treatment for reuse in power plants is not economically feasible above 30,000 mg/l TDS (discussed next).

Figure 8.2



Only basic chemistry is provided in the database, i.e. pH, sodium, potassium, calcium, magnesium, alkalinity, chloride and sulfate. Other chemical information of interest, such as silica, barium, ammonia, volatile organic constituents, etc. are not available except in individual analyses recovered from producers and published technical reports, e.g. Veil 2003 and ALL 2003. Of the 58,700 individual water analyses in the USGS database, 48,600 were deemed useable because their cation/anion balance was within ±5 percent of neutrality.

Given the limitations of the USGS database (along with its wealth of basic chemistry), a methodology is developed next to predict the capital and operating costs of produced water treatment.

8.3 Produced Water Treatability

It is assumed in this analysis that produced water is treated for reuse at a power plant that is reasonably close to conventional oil and gas or CBM production.[6] In some cases, low-TDS produced water could be used with minimal treatment in a power plant, i.e. requiring de-oiling and filtration. Although low-TDS produced water exists, its occurrence is relatively rare. This section develops costs for membrane and evaporative technologies (evaluated for SJGS) to treat a range of saline produced waters.

Lastly, it is assumed that waste streams generated by produced water treatment would either be:

- Mixed with power plant ash and/or SO_2 scrubber sludge and landfilled
- Disposed of in new evaporation ponds
- Brought to dryness via crystallization and landfilled with power plant ash and/or SO_2 scrubber sludge.

8.3.1 Treatment Technology

For this analysis, high-efficiency reverse osmosis (HERO®) and brine concentrator (BC) technologies (discussed in Deliverable 3, Treatment and Disposal Analysis) were used to evaluate produced water treatment. Three treatment configurations were evaluated:

- HERO® + BC
- HERO® + BC + evaporation ponds
- HERO® + BC + crystallizer

Refer to Figure 8.3. HERO®, BC and crystallizers are off-the-shelf technologies that have been used to treat high-TDS wastewater. The applicability of these configurations depends on how a power plant disposes of ash and SO_2 scrubber sludge and whether the climate is suitable for evaporation ponds. It is also assumed that reactor-clarifier sludge could be disposed of along with other treatment solids, since a $CaCO_3$-based waste product may not be suitable as a supplemental feedstock with all types of SO_2 scrubbers. Also, some plants might not have SO_2 scrubbers.[7]

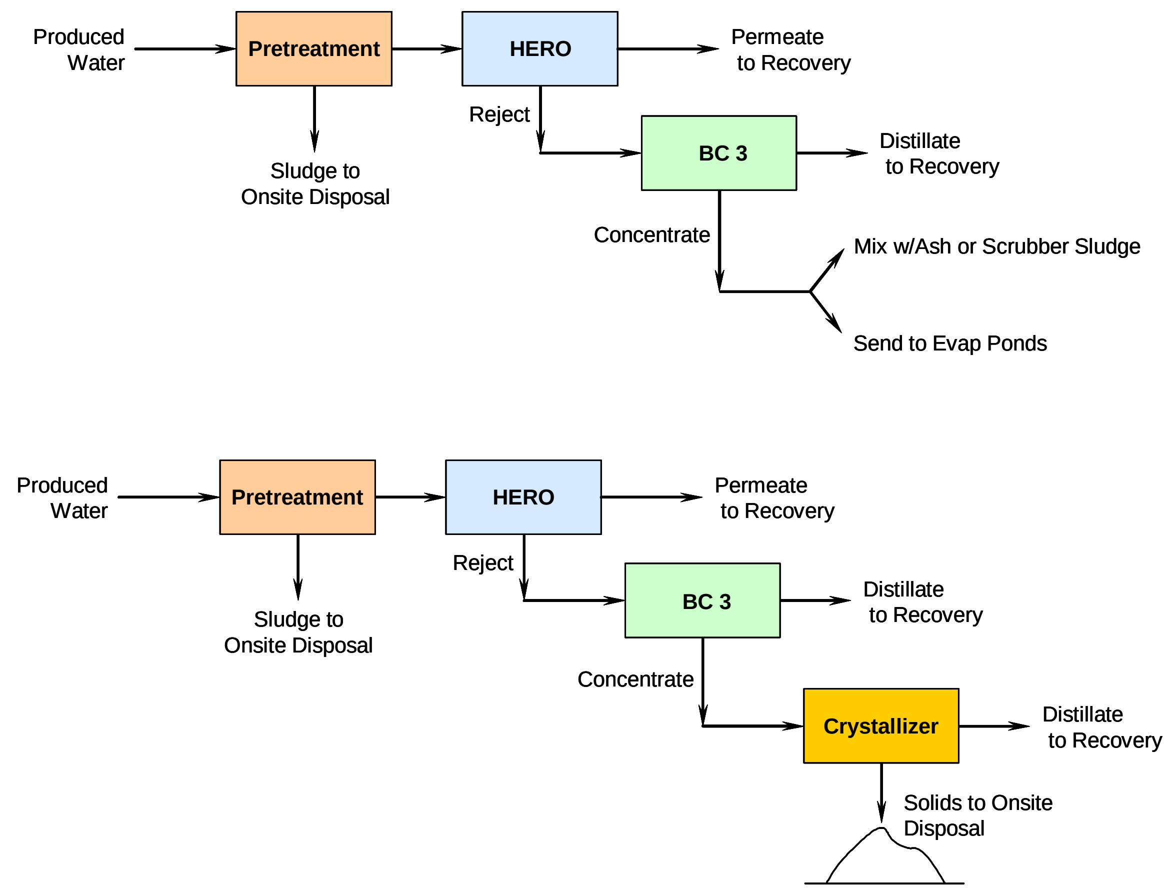
In this analysis, all equipment is assumed new, i.e. no existing equipment is reassigned or refurbished for produced water treatment service.

8.3.2 Treatability Criteria

Constituents evaluated for the treatability analysis are TDS, calcium, magnesium and alkalinity. These constituents drive the analysis because they determine the recovery parameters for treatment equipment as well as influencing operating parameters such as chemical consumption and power requirements.

[6] Recall that the 28.5-mile pipeline in the produced water assessment for SJGS was almost 45 percent of the total project cost.
[7] In Deliverable 3, Treatment & Disposal Analysis, we assumed that SJGS would feed reactor-clarifier sludge to the SO_2 absorbers as supplemental limestone feed.

Figure 8.3



Produced Water Treatment Configurations

The following general design criteria were used for the configurations outlined above:

- Reactor-clarifier solids are dewatered to 30 percent solids and landfilled onsite (with ash and/or SO_2 scrubber sludge)
- HERO® recovery is limited to 90 percent recovery or a reject concentration of 60,000 mg/l if 90 percent recovery is not achievable[8]
- BC recovery is limited to a brine concentration of 225,000 mg/l[9]
- The crystallizer is operated to produce a dry waste product consisting of 50 percent solids and landfilled onsite (with ash and/or SO_2 scrubber sludge).

Process criteria, although general, are closely associated with those used for the SJGS produced water project analysis.

The intent of this analysis is to maximize the recovery of the HERO® process and minimize the size of BC and crystallizer equipment and evaporation ponds. BC and crystallizer equipment is significantly more costly than the HERO® process (for a given flow rate) and more costly to operate. Evaporation ponds are capital intensive.

As outlined in Deliverable 3, HERO® pretreatment softening and high-pH operation are well suited to treat a variety of produced waters with high TDS, hardness, silica, traces of oil, etc. HERO® recovery is calculated as follows:

$$HERO\text{®}\ \mathrm{Recovery},\ \% = \left[1 - \frac{TDS_{Feed},\ mg/l}{60{,}000\ mg/l}\right] \times 100$$

For this analysis, the HERO® process is limited to a feedwater TDS limit of 30,000 mg/l and a recovery of 50 percent. If the feedwater TDS limit were raised to just 35,000 mg/l, allowable recovery would drop to 42 percent, and at 40,000 mg/l, recovery would only be 33 percent.

For example, if 50,000 BPD of produced water with a TDS of 12,000 mg/l were to be treated, the HERO® process would recover 80 percent of the feedwater as permeate (40,000 BPD). Refer to the summary below. The BC would treat the remaining 20 percent of HERO® reject (10,000 BPD). Since the HERO® would be operated at a maximum reject concentration of 60,000 mg/l and BC brine concentration would be set at 225,000 mg/l, the BC would recover 73.3 percent in all cases. Therefore, 7,330 BPD of HERO® reject would be recovered by the BC. This would leave 2,670 BPD of BC brine to either be landfilled with ash or scrubber sludge, sent to an evaporation pond, or treated further by a crystallizer to dry salts.

[8] HERO® reject is limited to the osmotic pressure rating of the membranes, which is equivalent to 70,000 to 75,000 mg/l of TDS. A conservative operating limit of 60,000 mg/l was selected. This slightly increases the size of the equipment that must be installed to reduce total wastewater volume to the brine concentrator and evaporation ponds or crystallizers.

[9] This assumes the BC is operated at a pH of 10.0 to 11.0 with no chloride limitation.

Stream	Flow Rate	TDS
Feedwater	50,000 BPD	12,000 mg/l
HERO® Permeate	40,000 BPD	<500 mg/l
BC Feedwater (HERO® Reject)	10,000 BPD	60,000 mg/l
BC Distillate	7,330 BPD	<10 mg/l
BC Brine	2,670 BPD	225,000 mg/l
Total Recovered	47,330 BPD	(94.7% Recovered)

8.3.3 Chemistry Assumptions

Refer to Figures 8.4, 8.5 and 8.6 for relationships between TDS and calcium, TDS and magnesium, and TDS and alkalinity, respectively. Emphasis was placed on evaluating calcium, magnesium and alkalinity relationships because the cost of pre-softening produced water with a reactor clarifier usually dominates all other chemical costs. The sheer volume of information in the USGS database established well-defined, dense envelopes for each relationship (17,100 datasets were within the TDS range of 0 to 30,000 mg/l).

Figure 8.4

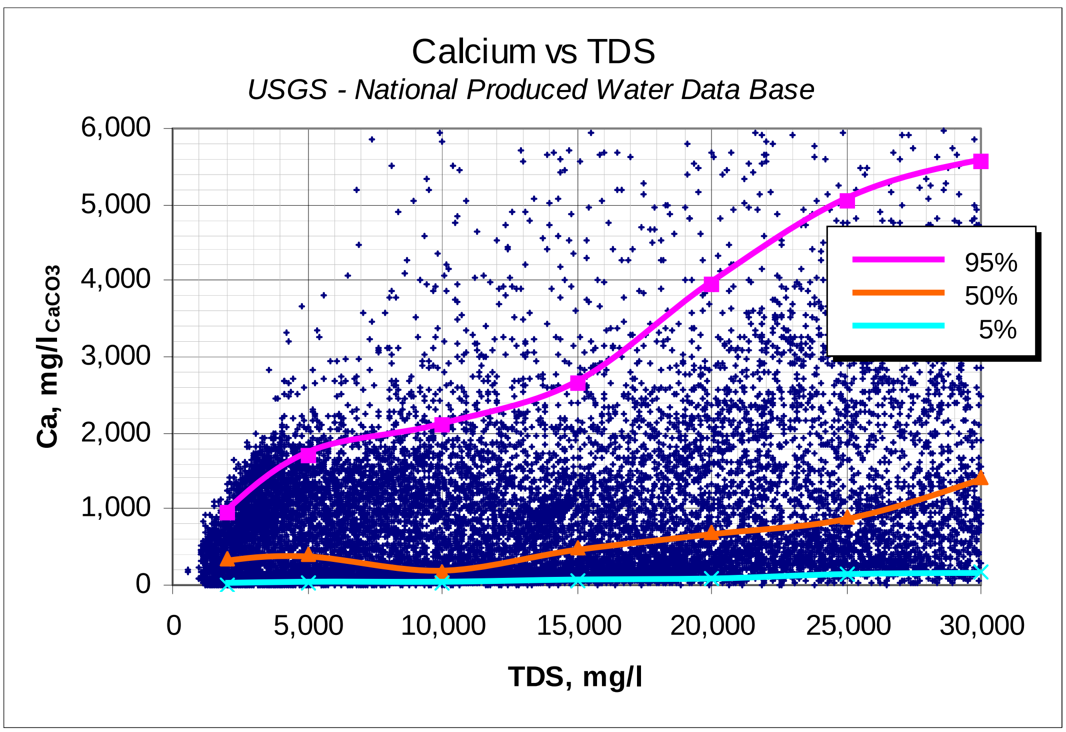


Figure 8.5

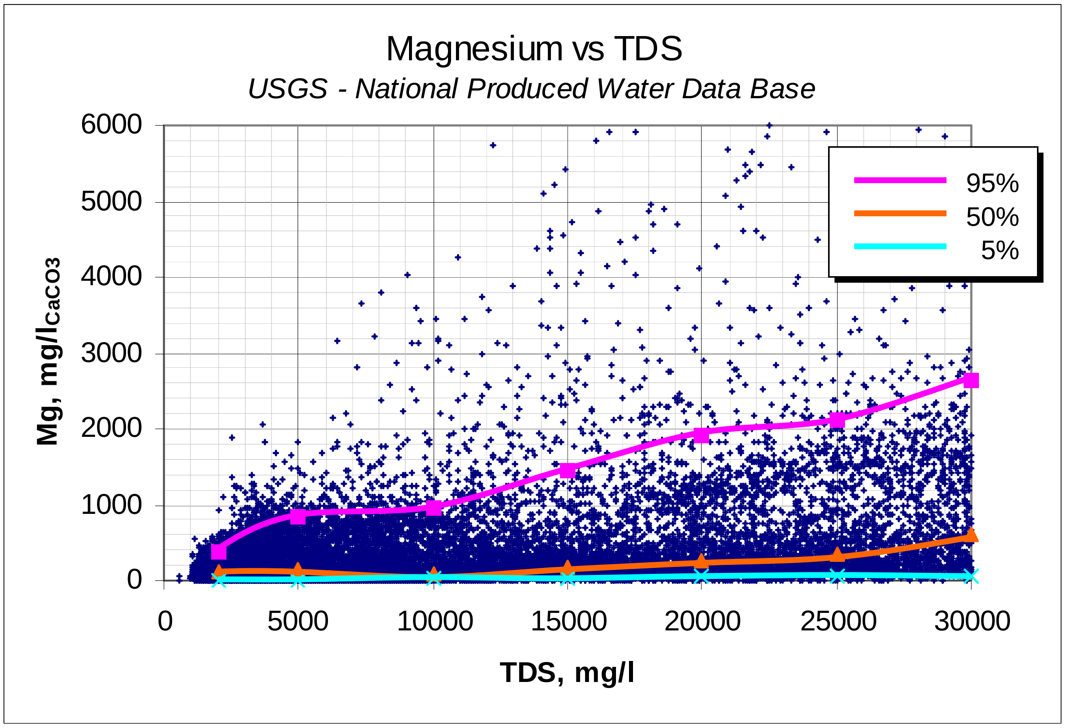
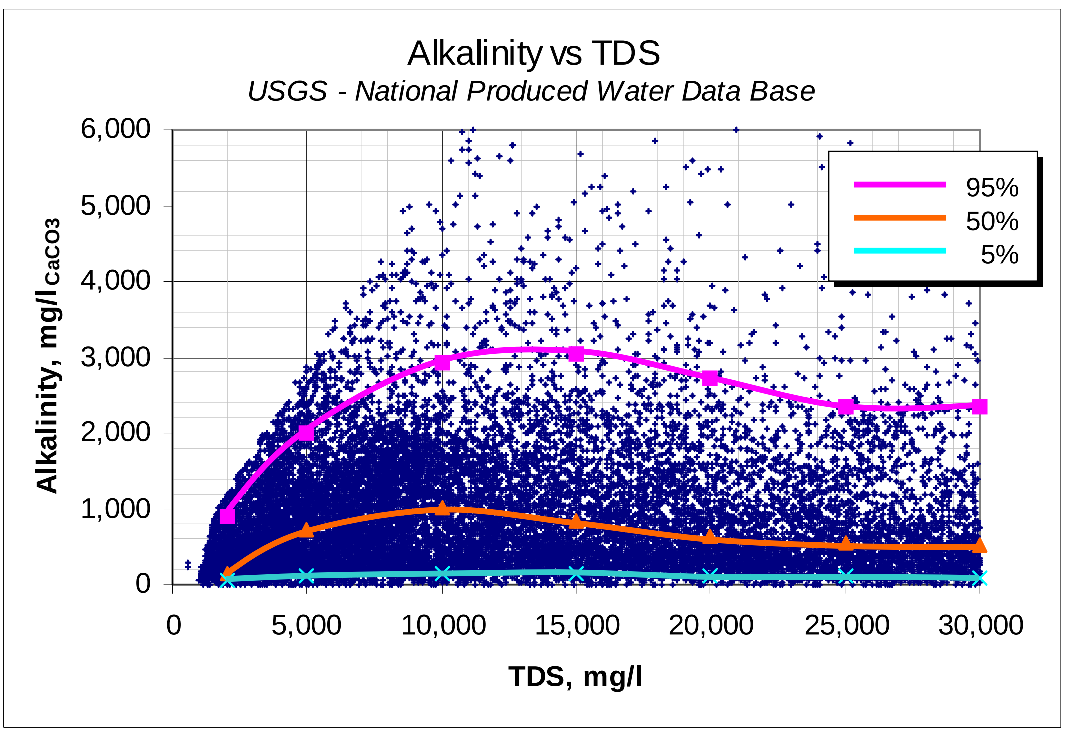


Figure 8.6



Seven TDS scenarios were established to determine the capital and operating cost of each treatment configuration – 2,000, 5,000, 10,000, 15,000, 20,000, 25,000 and 30,000 mg/l. For each TDS scenario, the data was assessed to find the 95-, 50- and 5-percentile[10] concentrations of calcium, magnesium and alkalinity. These values are roughly equivalent to maximum, mean and minimum values. The data summary for the seven TDS scenarios can be found in Table 8.2. For example, in the 10,000 mg/l TDS scenario[11], the 95-percentile calcium concentration was 2,110 mg/l_{CaCO3}, the 50-percentile calcium concentration was 190 mg/l_{CaCO3}, the 5-percentile calcium concentration was 34 mg/l_{CaCO3}.

The maximum concentration (100 percentile) for calcium, magnesium or alkalinity was not used in any of the TDS scenarios, because it was usually very high relative to the 95 percent value. For the 10,000 mg/l TDS scenario, the maximum value for calcium was 6,800 mg/l_{CaCO3} (3.2 times the 95-percentile value). Also, note that the 95-percentile value for calcium was usually 5 to 6 times that of the 50-percentile value (this applies to magnesium and alkalinity but at different levels of intensity). Conversely, the minimum concentrations (0 percentile) for calcium, magnesium and alkalinity were not used either, because all were 0 mg/l_{CaCO3}.

Table 8.2
Produced Water Chemistry – Data Summary

TDS mg/l	Percentile Concentrations								
	Ca, mg/l_{CaCO3}			Mg, mg/l_{CaCO3}			Alk, mg/l_{CaCO3}		
	95%	50%	5%	95%	50%	5%	95%	50%	5%
2,000	950	340	8	370	110	0	910	140	48
5,000	1,690	390	18	830	150	6	1,990	730	120
10,000	2,110	190	34	950	92	25	2,920	1,010	160
15,000	2,650	480	56	1,460	170	36	3,050	860	140
20,000	3,950	700	95	1,910	250	44	2,730	650	120
25,000	5,060	900	150	2,120	340	50	2,360	560	110
30,000	5,550	1,420	160	2,650	620	55	2,350	540	86

This data in Table 8.2 was used to evaluate a number of possible produced water chemistry and flow scenarios and is discussed in the next section.

8.4 Capital and Operating Cost of Produced Water Treatment

The chemistry developed in the previous section is used to assess a number of possible produced water flow and chemistry cases. Three treatment configurations (outlined previously) are evaluated for each TDS scenario and conceptual-level capital and operating costs are developed. Operating cost variations are bracketed to encompass the variability in the USGS database. The technology analysis in this section did not

[10] A 95 percentile value for calcium means that it is greater than 95 percent of all the calcium concentrations in a given TDS range.
[11] The 10,000 mg/l TDS scenario consists of calcium data within the TDS range of 9,001 to 10,000 mg/l. Depending on the scenario, the range was narrow (1,000 mg/l) for high-density areas within the data base and wider (2,000 mg/l) for less dense areas.

include equipment optimization, because optimization should be conducted when site-specific chemistry data is available.

Finally, no operating-cost offsets, as discussed in Deliverable 6, Cost/Benefit Analysis, were included in this analysis. For the SJGS produced water project, it was determined that a significant savings could be afforded by some of the producers, and those producers were willing to share the savings with Public Service of New Mexico (PNM)[12]. This approach is valid, however, this type of analysis is very site specific and should not be generally applied to all cases.

8.4.1 Capital Cost of Produced Water Treatment

This section of the deliverable presents costs for produced water treatment, de-oiling equipment and pipelines. No attempt was made to predict produced water gathering costs, because they are highly site specific and those costs would likely be borne by oil and gas producers. A number of flow and TDS scenarios were evaluated to determine the capital cost of a produced water project.

Produced Water Treatment Capital Costs

HERO®, BC and evaporation pond costs were factored from data obtained for Deliverable 6, Cost/Benefit Analysis and previous work with PNM. Costs for crystallizers were obtained from equipment suppliers, information the author developed in previous work and with PNM. Three treatment configurations were evaluated:

- HERO® + BC
- HERO® + BC + evaporation ponds
- HERO® + BC + crystallizer

Refer to Figures 8.7 through 8.9 for the capital cost of each configuration for a range of feedwater rates (10,000 BPD to 100,000 BPD) and seven different TDS scenarios ranging from 2,000 mg/l to 30,000 mg/l. The costs include equipment and installation plus 25 percent contingency to cover project unknowns. Refer to Table 1 in Appendix A for capital cost assumptions. Because this analysis is general (not specific to any particular site), costs should be considered "conceptual level" with a +50/-35 percent range of confidence. In other words, the capital costs derived from Figures 8.7 through 8.9 could be 50 percent greater or 35 percent less than the actual cost of installation.

Note that, at produced water TDS levels in excess of 20,000 mg/l, the cost of the equipment in scenarios with BCs and crystallizers jumps notably. In scenarios involving evaporation ponds, the cost variation is not as pronounced. Generally, as HERO® recovery drops at higher TDS levels, BC and crystallizer equipment and evaporation ponds must be sized larger. For example, if produced water TDS were 40,000 mg/l, the BC would be 50 percent larger than a HERO® operating with a feedwater TDS at 30,000 mg/l. For the purpose of this analysis, the economic TDS limit was established at 30,000 mg/l.

[12] PNM operates and is a partial owner of SJGS.

Figure 8.7

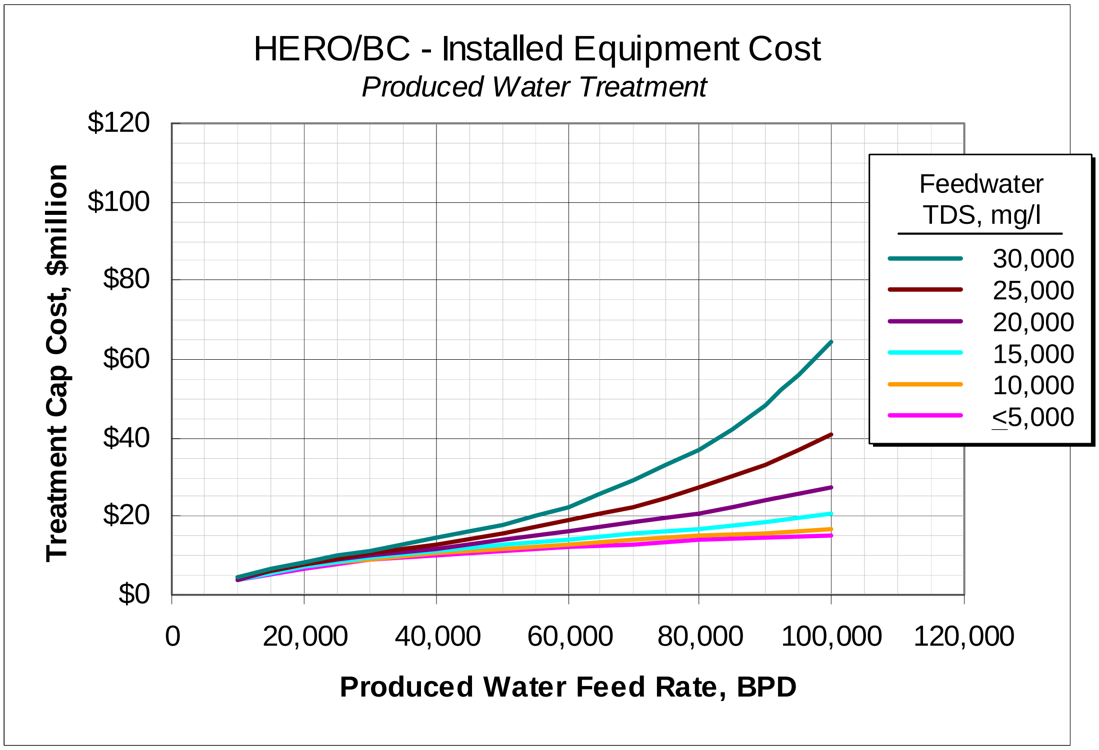


Figure 8.8

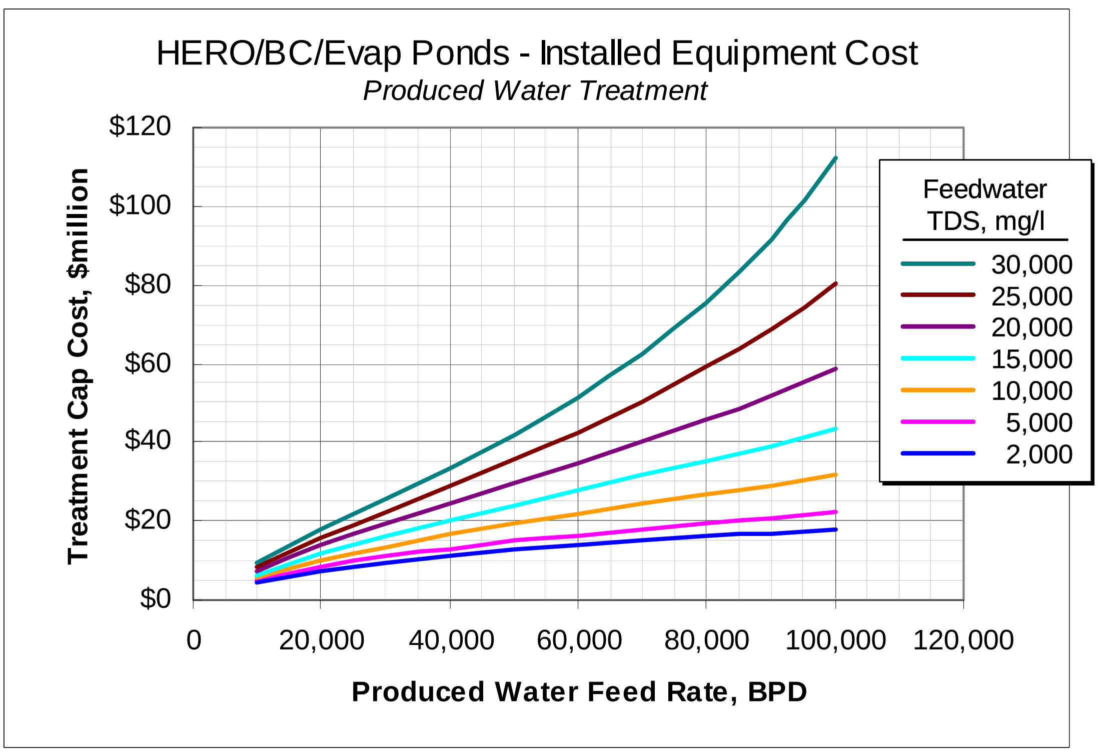
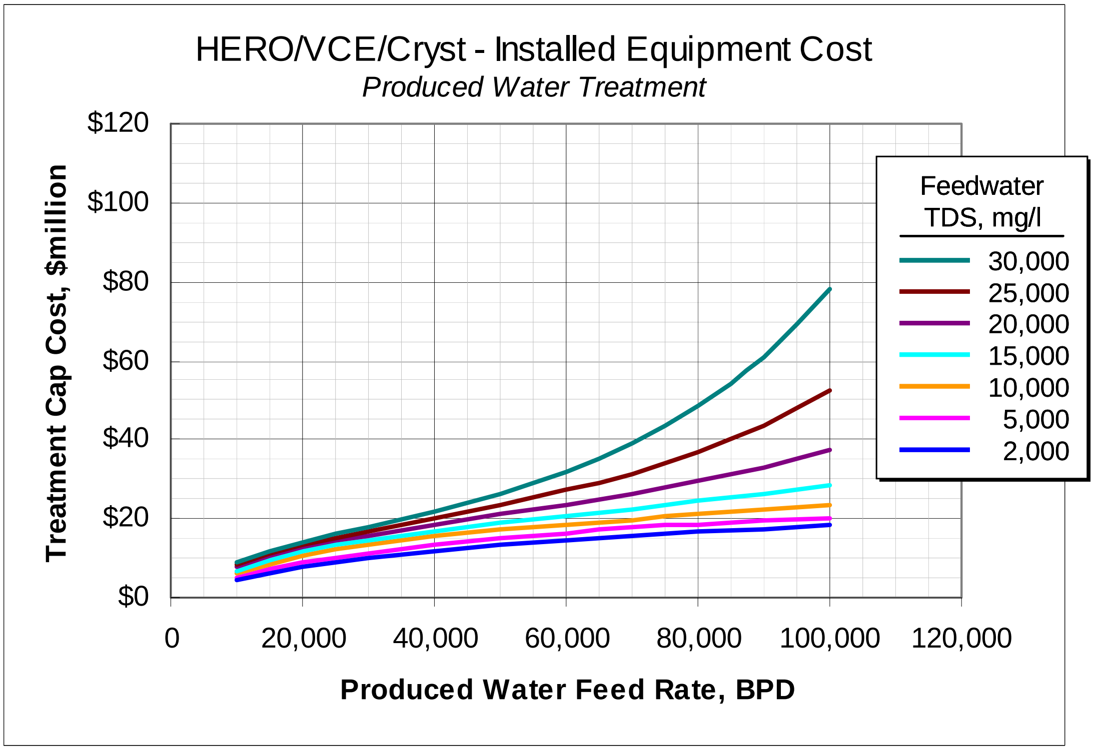


Figure 8.9



De-Oiling and Filtration Capital Costs

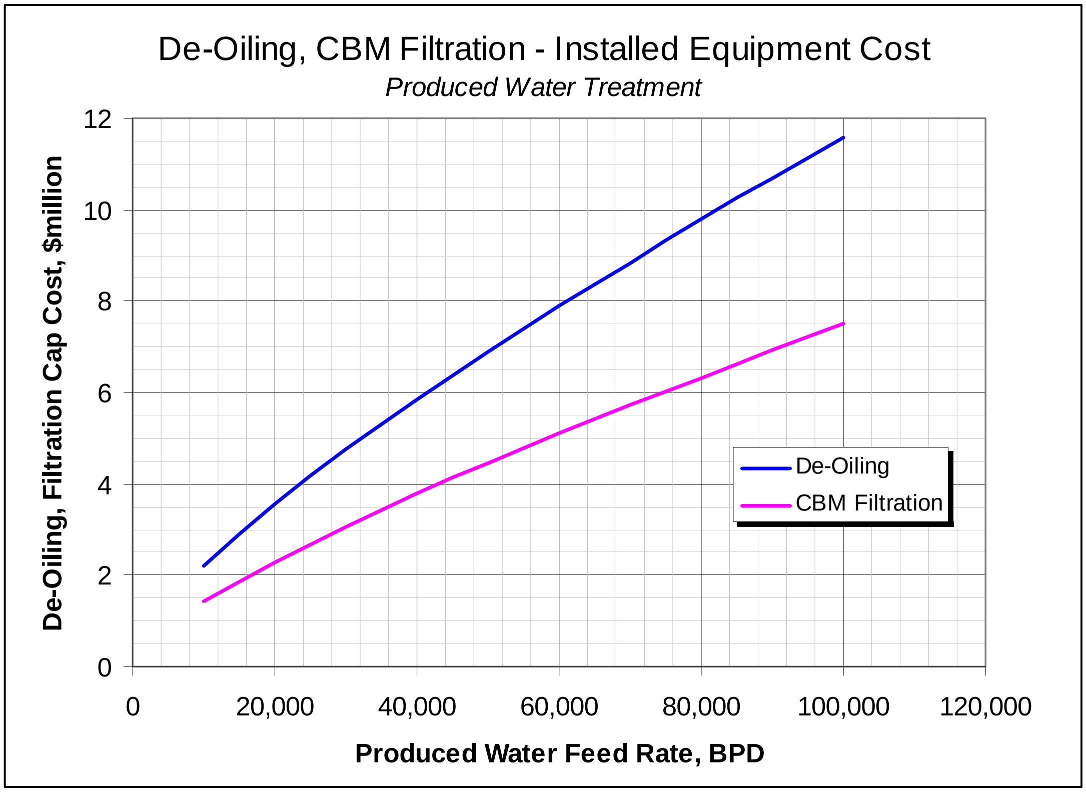
De-oiling equipment is only applicable to conventional oil and gas production in this analysis. Refer to Deliverable 3, Section 3.5, Collection Center in Bloomfield and Figure 3.10 for a process description and schematic for de-oiling equipment. The only exception would be covered tanks instead of the open basins proposed for SJGS. Some produced water could create a safety problem (and public nuisance) because of elevated levels of hydrogen sulfide gas (H_2S).[13] The occurrence of H_2S is highly site specific and cannot be predicted from the information in the USGS database.

CBM produced water is free of oily byproducts found in conventionally produced water, but typically contains coal fines. For this analysis, the process schematic would be similar to de-oiling but without gravity separation, oil recovery, gas flotation and off-spec produced water management.

Refer to Figure 8.10 for de-oiling equipment (conventional production) costs and filtration equipment (CBM production) costs.[14] Lastly, it is assumed that the de-oiling or filtration equipment is located at the produced water treatment plant.

[13] Open basins were acceptable for the SJGS produced water project because H_2S is typically at non-detectable levels.
[14] The costs for de-oiling and filtration equipment are not effected by produced water TDS.

Figure 8.10



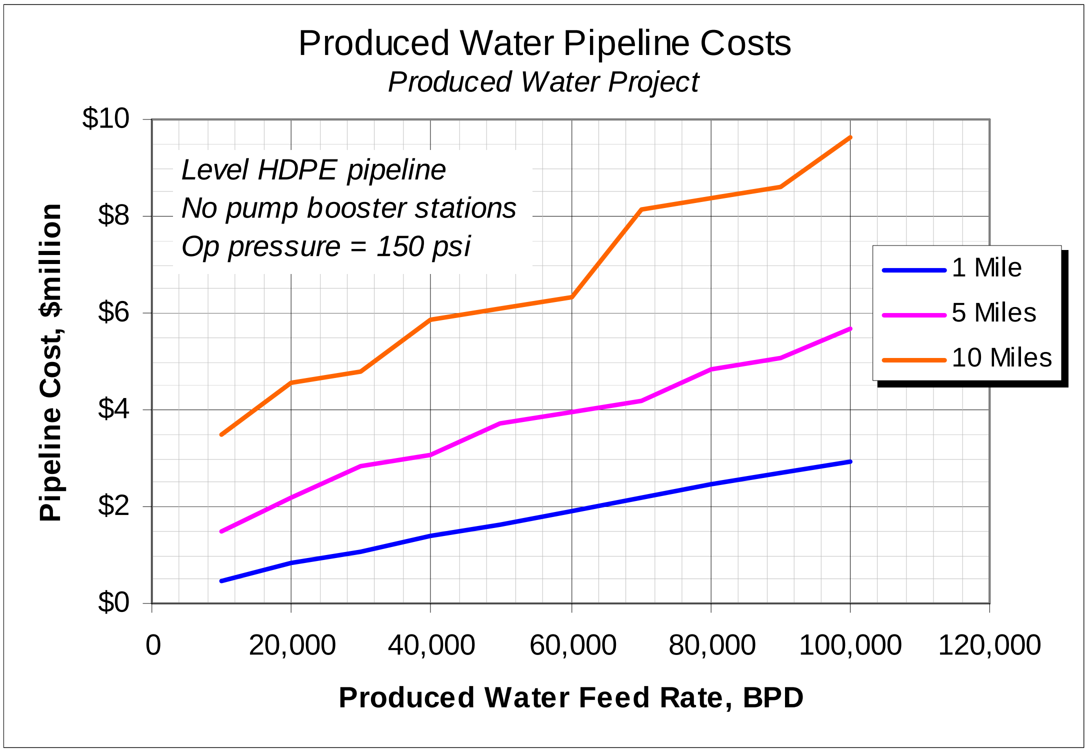
Pipeline Capital Costs

Refer to Figure 8.11 for an estimate of pipeline costs. Three scenarios are presented – one, five and ten-mile pipelines. To simplify the analysis, the pipelines were assumed to be over flat terrain (no intermediate pump stations), constructed with HDPE[15] and operated at a relatively low pressure (to accommodate the HDPE). The pipeline headworks would consist of two tanks capable of holding 12 hours of daily inflow, one to three clean-out stations (pigging equipment), and a pump station to charge the line.

Cost criteria developed for the SJGS produced water pipeline were used in this analysis. For SJGS, it was determined that a pipeline would cost from $6.00 to $9.00 per inch-diameter per linear foot depending on the route. An average value of $7.50/inch-D/foot was used in this analysis. The step-features of the cost lines are a result of line-size changes, i.e. the diameter of the line was increased at higher flow rates to minimize pressure drop. Costs were developed separately for the collection tanks and pump station (located at the head works) and were incorporated into the graphical analysis.

[15] HDPE is high-density polyethylene – plastic pipe used for low-pressure corrosive-water service.

Figure 8.11



8.4.2 Operating Cost of Produced Water Treatment

For each of the seven TDS scenarios, 27 combinations of calcium, magnesium and alkalinity concentrations were assessed.[16] The chemistry derived from the USGS Produced Waters Database and presented in Table 8.2 provided the basis for the analysis. As stated previously, this analysis was designed to determine the performance and operating cost of a reactor clarifier. Since calcium, magnesium and alkalinity concentrations are lowered in a reactor clarifier, TDS was adjusted[17] to predict HERO® recovery and subsequently size the BC, crystallizer and evaporation ponds.

The chemical costs for the reactor clarifier, which typically dominate other chemical costs, were also averaged and added to the cost of other chemicals, power, membrane replacement, cleaning (RO membranes, BC internal surfaces and crystallizer internal surfaces as applicable), sludge/solids handling and onsite disposal, labor, and maintenance. Refer to Figures 8.12 through 8.14. Staffing to operate and maintain the treatment plant was also adjusted (to determine labor costs) based on the size of the plant. Refer to Table A.1 in Appendix A for operating cost assumptions.

[16] Three constituents (calcium, magnesium and alkalinity) by three concentrations (95-, 50- and 5-percentile) for a total of 27 combinations.

[17] When softening occurs in a reactor clarifier, effluent concentrations for calcium, magnesium and alkalinity are lowered, and depending on the chemicals used, sodium can increase. For each case within a scenario, TDS was recalculated. Then the 27 values were averaged to determine adjusted TDS (used to calculate HERO® recovery). This averaging method, although it reduces the case-by-case variability in the adjusted TDS, is more representative than the unadjusted value.

Operating costs in Figures 8.12 through 8.14 do not include capital recovery costs. These costs were purposely left out to show how throughput capacity and TDS affect unit operating costs. Additionally, since there is no standard method to determine capital recovery, this calculation is left to the reader.

Unit operating costs are expressed as dollars per barrel ($/bbl). Therefore, in Figure 8.12, for a 50,000 BPD plant with a produced water TDS of 10,000 mg/l, the unit operating cost would be $0.14/bbl to operate a HERO® and BC. This translates to an operating cost of $7,000 per day (50,000 BPD x $0.14/bbl) or $2,555,000 per year. The costs include chemicals, power, membrane replacement, HERO® and BC cleaning, reactor-clarifier sludge handling and onsite disposal, labor, and maintenance.

Figures 8.15 and 8.16 were developed to show what the variation could be to the calculated operating cost. The differences are based on the variation created by the 5- and 95-percentile calcium, magnesium and alkalinity concentrations. For these charts, a cost factor of 1.0 is equivalent to the operating costs found in Figures 8.12 through 8.14 (~50-percentile values). For the same example, the minimum and maximum operating cost factors from Figure 8.15 are 0.63 and 2.35, respectively. This translates to an operating cost range of $0.09/bbl ($0.14/bbl x 0.63) to $0.33/bbl ($0.14/bbl x 2.35). If the calcium, magnesium and alkalinity are known, the operating cost range could be roughly interpolated. It is prudent to apply variations to general data until site-specific information can be assessed.

Lastly, the cost range is large because of the significant degree of calcium, magnesium and alkalinity variation in the USGS database. It should be noted that 50-percentile (mean) concentrations are much closer to the 5-percent concentrations than 95-percentile. Again, site-specific chemistry is required to rigorously evaluate treatability and costs. The approach developed here can be used to <u>conceptually bracket operating costs</u>.

<u>De-Oiling and Filtration Operating Costs</u>

The unit operating cost for this analysis[18] for de-oiling conventional oil and gas produced water is $0.035/bbl. The calculated values over the range of feedwater throughput vary little from a small to large de-oiling systems. Refer to Table A.1 in Appendix A for operating cost assumptions. The unit cost includes power, maintenance, chemicals and offsite transportation and disposal of off-spec produced water. Because of the unknowns, no recovered-oil credit was taken. Note that off-spec produced water disposal comprises 40 percent of the operating cost.

The unit operating cost for CBM water filtration is $0.014/bbl (applicable to small and large systems as well). Labor for de-oiling and CBM filtration was included in the produced water treatment plant staffing assumptions.

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[18] The analysis incorporated most of the assumptions used for the Bloomfield Collection Center for the SJGS produced water project. Refer to Deliverable 3, Section 3.5.

Figure 8.12

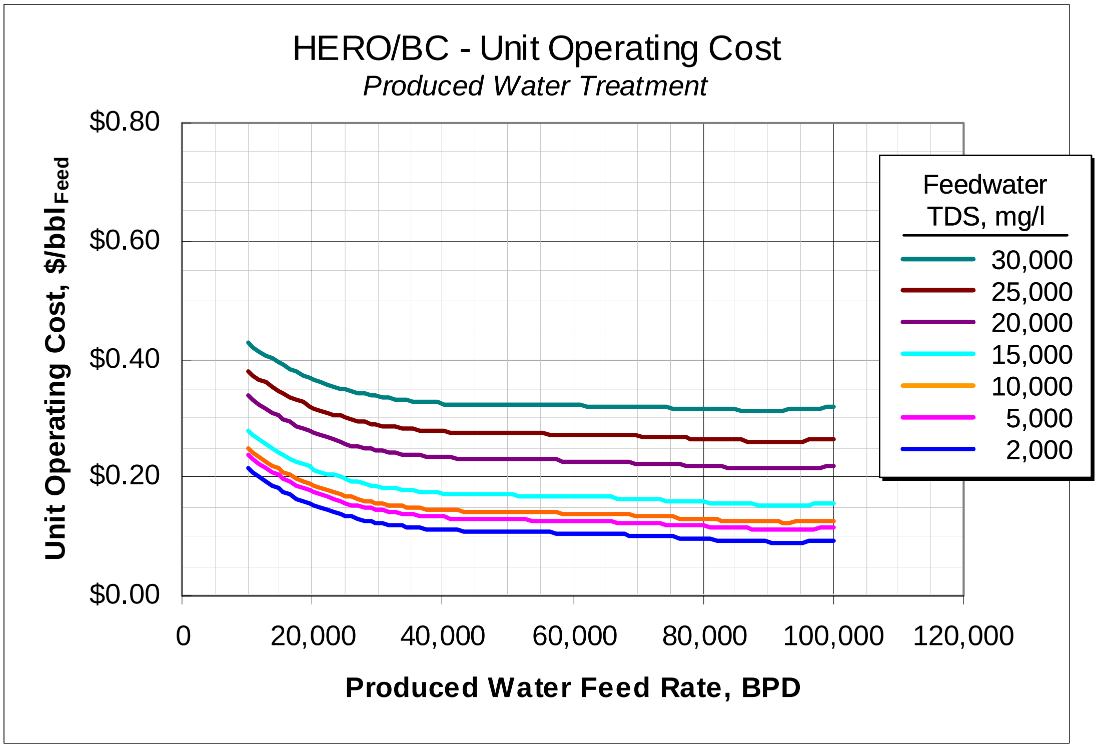


Figure 8.13

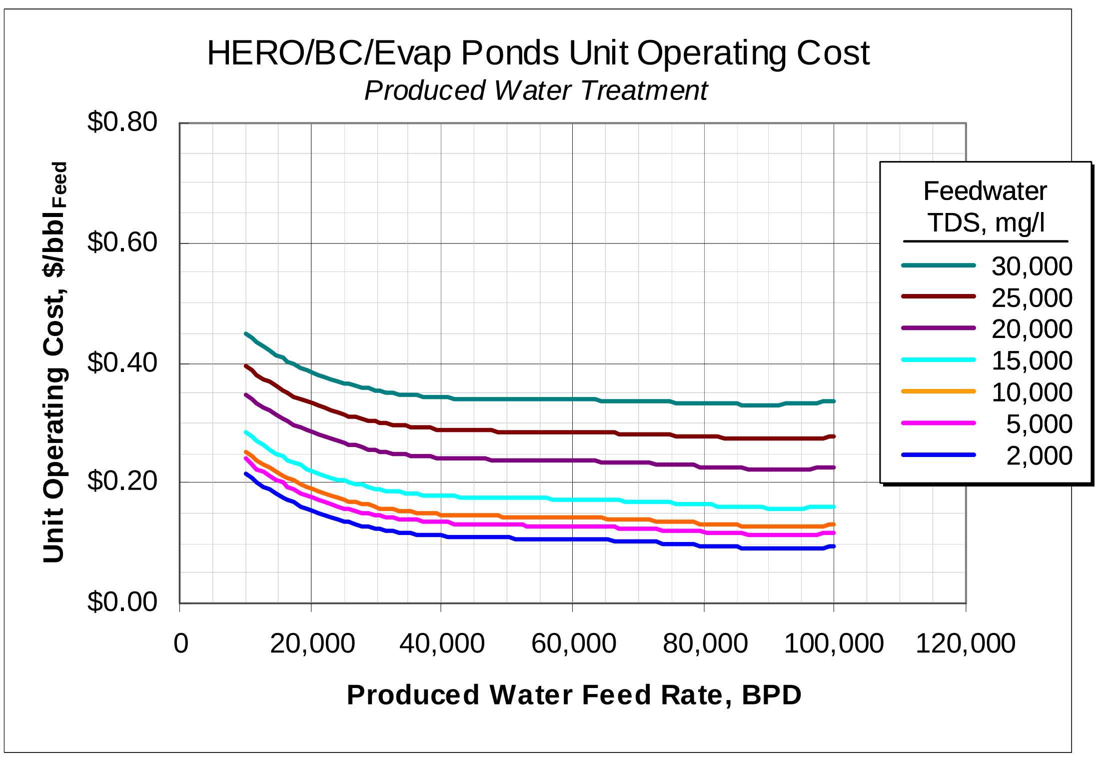


Figure 8.14

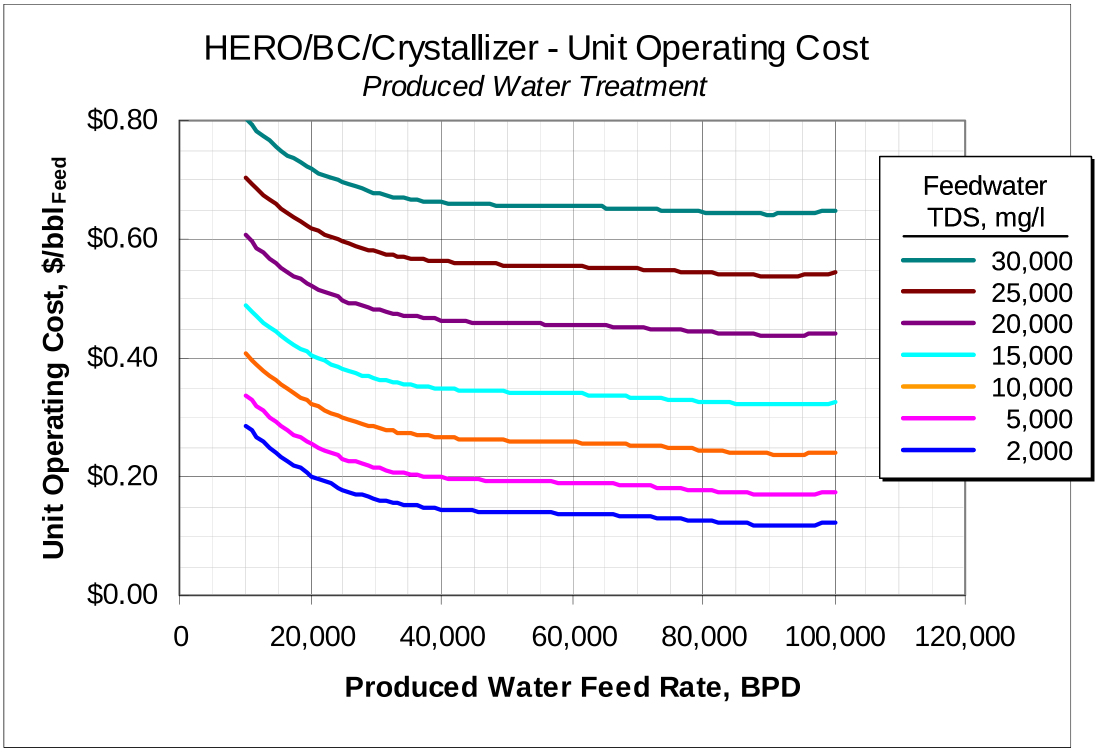


Figure 8.15

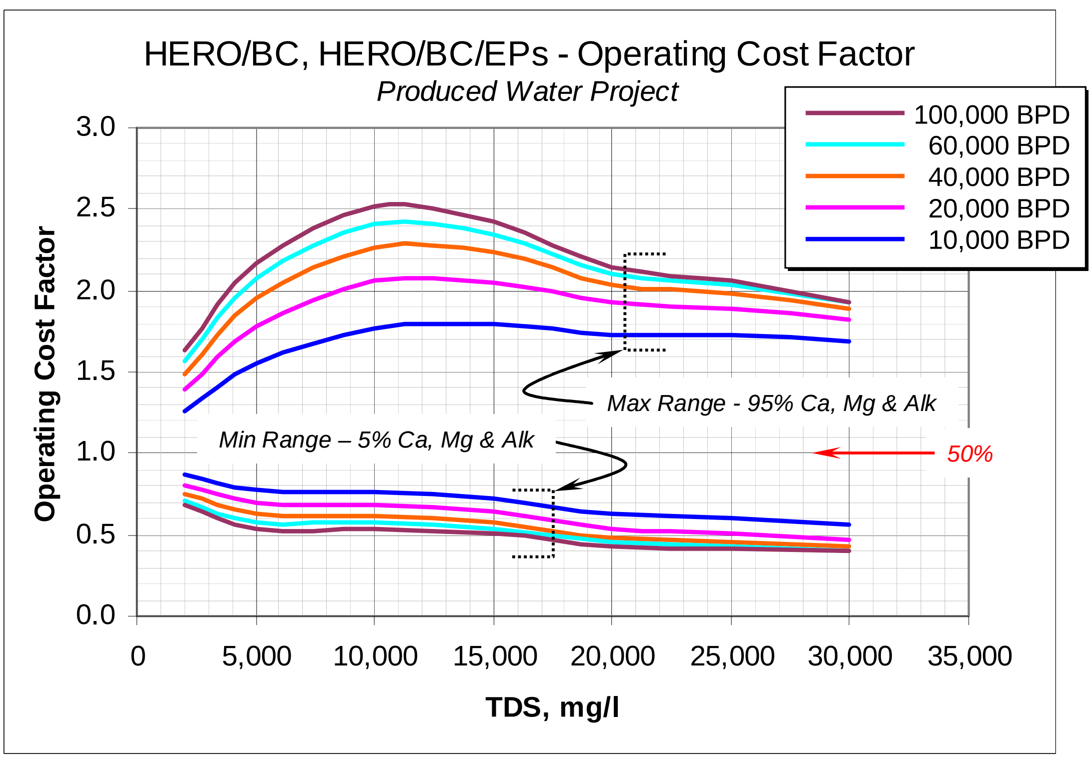
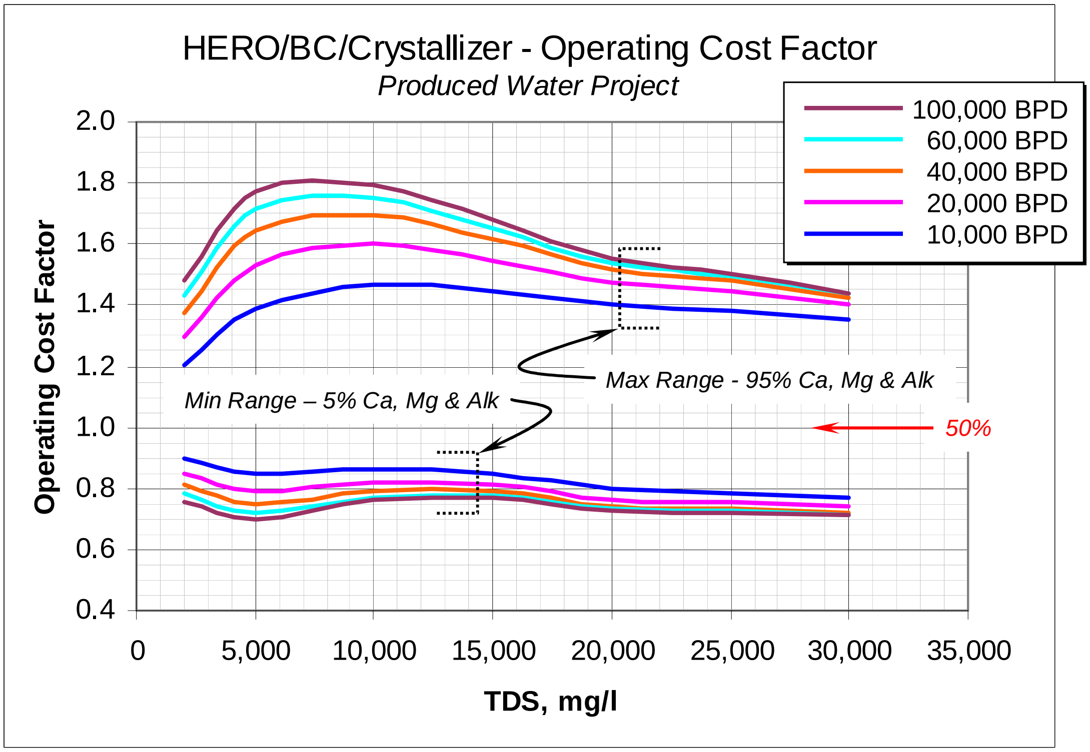


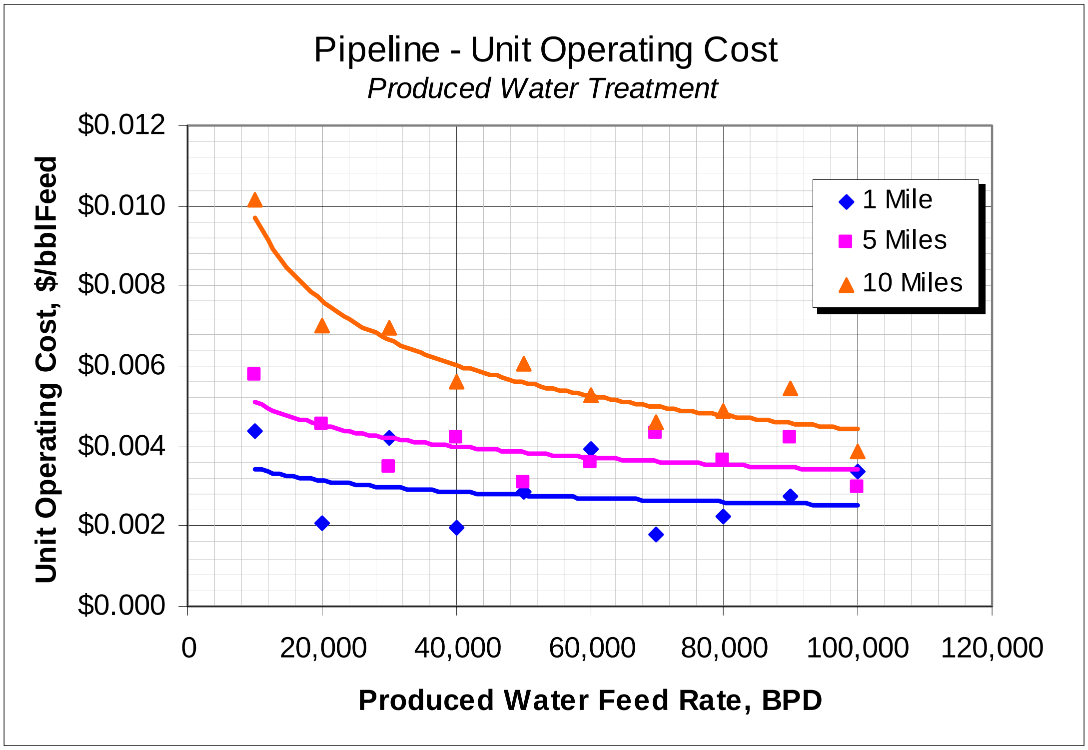
Figure 8.16



<u>Pipeline Operating Costs</u>

Pipeline operating costs are presented in Figure 8.17 (the analysis was smoothed with a curve fitting tool). The costs include pumping power and maintenance. Refer to Table A.1 in Appendix A for operating cost assumptions. Point-to-point cost variation is high in this analysis as a result of pipeline charging pressure. Line size selection and flow rate have a significant effect on pipeline pressure drop since transitions to larger diameter lines sizes are step-like and not smooth. Pipeline labor was included in the produced water treatment plant staffing assumptions.

Figure 8.17



8.5 Plant Examples

Two plant examples are presented to show how the cost estimating charts could be used to evaluate conceptual-level produced water capital and operating costs.

8.5.1 Site 1 Example

A coal-fired power plant in the Southwest is approximately 7.5 miles from conventional oil production. The plant has an opportunity to treat and use 60,000 BPD of produced water with a TDS of 12,000 mg/l that would otherwise be disposed via injection. Assume that the existing de-oiling equipment (operated by the producers) is quite old and unreliable, so new equipment would be installed with the produced water treatment plant. The power plant has also determined that wastewater generated by produced water treatment must be sent to an evaporation pond. Table 8.3 describes the capital and operating cost elements of the analysis. Total installed cost is projected to be $37,200,000 for the produced water treatment plant, de-oiling equipment and a pipeline. Recall that the capital cost should be considered “conceptual level” with a +50/-35 percent range of confidence. Operating costs are expected to be within a range of $0.128/bbl to $0.426/bbl – this cost will be a function of produced water quality. Operating costs include chemicals, power, membrane replacement, equipment cleaning, maintenance and labor. Recall that the operating cost does not include capital recovery.

Table 8.3
Cost Analysis – Example 1

Design Basis			
Throughput	60,000 BPD		
Produced Water TDS	12,000 mg/l		
Distance to Source	7.5 miles		
Ultimate Disposal	Evaporation Pond		
Installed Cost Analysis			
Produced Water Treatment (Figure 8.8)	$24,000,000		
De-Oiling (Figure 8.10)	$8,000,000		
Pipeline (Figure 8.11)	$5,200,000		
Total Installed Cost (1)	$37,200,000		
Unit Operating Cost			
Mean Produced Water Treatment (Figure 8.13)	$0.16/bbl		
Cost Variation Factors (Figure 8.15)	0.55 (5 percentile)	2.41 (95 percentile)	
	Min	Mean	Max
Produced Water Treatment	$0.088/bbl	$0.160/bbl	$0.386/bbl
De-Oiling (same for all scenarios)	$0.035/bbl	$0.035/bbl	$0.035/bbl
Pipeline (Figure 8.17)	$0.005/bbl	$0.005/bbl	$0.005/bbl
Total Unit Operating Cost ($\$/bbl_{Feed}$)	$0.128/bbl	$0.200/bbl	$0.426/bbl
Annual Operating Cost (2)	$2,800,000	$4,380,000	$9,330,000

Notes…..

1. Recall that the capital cost should be considered “conceptual level” with a +50/-35 percent range of confidence.
2. Does not include capital recovery costs.

Note, if the calcium, magnesium and alkalinity concentrations in the produced water were determined to be close to the mean values found in Table 8.2 (or Figures 8.4 through 8.6), the operating cost would be close to $0.200/bbl. Therefore, knowing basic site-specific chemistry can be useful in narrowing the range of the operating costs by roughly interpolating the cost factor in Figures 8.15 and 8.16.

8.5.2 Site 2 Example

A coal-fired power plant in a Rocky Mountain state is approximately 2.5 miles from CBM production. They have an opportunity to treat and use 40,000 BPD of produced water with a TDS of 6,000 mg/l that would otherwise be disposed of. Assume that the existing filtration equipment (operated by the producers) is quite new, so filters would not be installed at the produced water treatment plant. The power plant has also determined that produced water treatment wastewater must be sent to crystallizers. The dried waste would be landfilled along with scrubber sludge. Table 8.4 describes the capital and operating cost elements of the analysis. Total installed cost is projected to be $15,000,000 for the produced water treatment plant and a pipeline. Operating costs are expected to be within a range of $0.169/bbl to $0.371/bbl.

Table 8.4
Cost Analysis – Example 2

Design Basis			
Throughput	40,000 BPD		
Produced Water TDS	6,000 mg/l		
Distance to Source	2.5 miles		
Ultimate Disposal	Crystallizer		
Installed Cost Analysis			
Produced Water Treatment (Figure 8.9)	$13,000,000		
De-Oiling (Figure 8.10)	N/A		
Pipeline (Figure 8.11)	$2,000,000		
Total Installed Cost (1)	$15,000,000		
Unit Operating Cost			
Mean Produced Water Treatment (Figure 8.14)	$0.22/bbl		
Cost Variation Factors (Figure 8.15)	0.75 (5 percentile)	1.67 (95 percentile)	
	Min	Mean	Max
Produced Water Treatment	$0.165/bbl	$0.220/bbl	$0.367/bbl
De-Oiling (same for all scenarios)	N/A	N/A	N/A
Pipeline (Figure 8.17)	$0.004/bbl	$0.004/bbl	$0.004/bbl
Total Unit Operating Cost ($\$/bbl_{Feed}$)	$0.169/bbl	$0.226/bbl	$0.371/bbl
Annual Operating Cost (2)	$2,470,000	$3,300,000	$5,360,000

Notes…..
1. Recall that the capital cost should be considered "conceptual level" with a +50/-35 percent range of confidence.
2. Does not include capital recovery costs.

Again, if the calcium, magnesium and hardness concentrations in the produced water were determined to be close to the mean values found in Table 8.2, the operating cost would be close to $0.226/bbl.

8.6 Summary

Nationally, produced water volume is dropping along with reduced conventional oil and gas production. New CBM development should dampen the decline in produced water volume in a number of states where there are large coal reserves such as Colorado, Wyoming and Montana. Seven states generated 90.1 percent of the produced water in 2002. Texas alone generated 35.5 percent of the produced water in the US during the same year.

USGS has compiled a Produced Waters Database. One of the important values of the data is that it shows the variability of the produced water resource. For example, produced water TDS in the database ranges from 500 mg/l to 400,000 mg/l. About 37 percent of the produced water sources in the database have a TDS value of less than 30,000 mg/l. This is significant because produced water treatment for reuse in power plants is not economically feasible above 30,000 mg/l TDS. Only basic chemistry is provided in the database, i.e. pH, sodium, potassium, calcium, magnesium, alkalinity, chloride and sulfate. Other chemical information of interest, such as silica, barium, ammonia, volatile organic constituents, etc. are not available.

High-efficiency reverse osmosis (HERO®) and brine concentrator (BC) technologies were evaluated for produced water treatment:

- HERO® + BC (waste brine disposed with ash and/or SO_2 scrubber sludge)
- HERO® + BC + evaporation ponds
- HERO® + BC + crystallizer

The applicability of these treatment systems depends on how a power plant is configured with respect to ash and SO_2 scrubber sludge disposal and whether the climate is suitable for evaporation ponds. It is also assumed that reactor-clarifier sludge could be combined with other treatment solids for disposal. In this analysis, all equipment was assumed to be new, i.e. no existing equipment is reassigned or refurbished for produced water treatment service.

The analysis was biased to maximize the recovery of the HERO® process and minimize the size of BC and crystallizer equipment and evaporation ponds. BC and crystallizer equipment is significantly more costly to install than the HERO® process (for a given flow rate) and more costly to operate. Evaporation ponds are capital intensive.

Capital cost was predicted for each configuration, for a range of feedwater rates (10,000 BPD to 100,000 BPD), and for seven different TDS scenarios ranging from 2,000 mg/l to 30,000 mg/l. The costs include equipment and installation plus 25 percent contingency to cover project unknowns. Also, because this analysis is general (not specific to any particular site), costs should be considered “conceptual level” with a +50/-35 percent range of confidence.

Operating costs were developed for each of the seven TDS scenarios. The analysis was designed to determine the performance and operating cost of a reactor clarifier, since its costs typically dominate other chemical costs. Reactor clarifier costs were averaged and added to the cost of other chemicals, power, membrane replacement, cleaning (RO membranes, BC internal surfaces and crystallizer internal surfaces as applicable), sludge/solids handling and onsite disposal, labor, and maintenance. Staffing to operate and maintain the treatment plant was adjusted (to determine labor costs) based on the size of the plant. Lastly, operating costs did not include capital recovery costs. These were purposefully left out to show how throughput capacity and TDS affect unit operating cost.

Adjustment factors are provided to determine the variability of operating costs. It is prudent to apply variations to general data until site-specific information can be assessed. Site-specific chemistry is required to rigorously evaluate treatability and costs. The approach developed here can be used to conceptually bracket operating costs.

Capital and operating costs for de-oiling/filtration facilities and three pipeline scenarios were also estimated separately.

Two plant examples are presented to show how the cost estimating charts could be used to evaluate the treatment of produced water at power plants close to oil and/or gas production.

Appendix A

Table A.1

Capital and Operating Cost Assumptions

Produced Water Project

Chemical Costs…..			
93% $Ca(OH)_2$, $/ton		$86	
98% Na_2CO_3, $/ton		$100	
93% H_2SO_4, $/ton		$91	
50% NaOH, $/ton		$78	Dry basis cost
Other Chemical		15%	of major chemicals
Reactor Clarifier, BC, Crystallizer Op Assumptions.....			
RC Sludge Moisture Content		30%	
Crystallizer Solids Moisture Content		50%	
On-Site Sludge & Solids Disposal, $/ton		$25	
HERO Final Reject TDS, mg/l		60,000	or 90% recovery if less than 60,000 mg/l
HERO Operating pH		10.0	
BC Operating pH		10.5	
Excess WAC H_2SO_4		20%	
BC Brine Total Solids, mg/l		225,000	
RO/VCE/Crystallizer cleanings……			
	Annual Freq	Cost per Cleaning	
RO	1	$10,000	
VCE	0.66	$30,000	
Crystallizer	1.5	$30,000	
HERO membrane replacement	-----	$180,000	40,000 BPD basis
Equipment Power Requirements…..			
HERO System, kwh/kgal		7.0	Feedwater basis - includes 5% allowance for misc power
BC, kwh/kgal		78.1	Distillate basis - includes 2% allowance for misc power
Crystallizer, kwh/kgal		303.7	Feedwater basis - includes 2% allowance for misc power
Power Cost, $/kwh		$0.050	
Labor assumptions…..			
Fully Burdened Labor Costs, $/hour		$50	
Full Time Coverage, hours/year		8,760	

	<40,000 BPD	<80,000 BPD	<100,000 BPD
Operators…..			
HERO/VCE, hours/year	6,240	8,320	10,400
Crystallizer, hours/year	2,080	2,080	2,080
De-Oiling & Pipeline, hours/year	1,040	1,040	1,040
Maintenance & Instrument Techs…..			
HERO/VCE, De-Oiling & Pipeline, hours/year	2,600	2,600	2,600
Crystallizer, hours/year	1,040	1,040	1,040

De-Oiling System…..		
Tank Insulation	Yes	
Tank Heaters	Yes	
Off-Spec Water Fraction	0.2%	of daily in-flow
Off-Spec Water Hauling Cost, $/bbl	$1.00	
Off-Spec Water Disposal Cost, $/bbl	$6.50	
Credit Taken for Recovered Oil	None	
Pipeline…..		
Unit Pipeline Cost, $/inch-Dfoot	$7.50	
Pipeline Material	HDPE	
Pipeline Max Operating Pressure, psi	150	
Pipeline Pump Stations	0	
Route Type	City/Open Country	
Terrain Type	Flat	
Evaporation Ponds…..		
Evap Pond Installed Cost, $/acre	$200,000	
Annual Avg Evap Rate, gpm/acre	2.0	Equivalent to ~40" net evaporation per year
Installation Cost Factor.....	45%	of process equipment equipment costs
De-Oiling, HERO Eqpmt Maintenance Cost	2.0%	of equipment costs
Evap Pond Maintenance Cost	0.5%	of evaporation pond cost
Pipeline Maintenance Cost	1.5%	of installed cost
Capital Cost Contingency	25%	of equipment costs